FINAL REPORT

for

FAA GRANT 97-G-006

Application of Smart Structures Technology to Aircraft

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Summary

The objective of this research was to develop applications of segmented piezoelectric and piezoceramic components for the motion analysis, health monitoring and damage detection in aircraft structures. This work was proposed as the continuation of our earlier research previously funded by the FAA Center of Excellence for the Computational Modeling of Aircraft Structures at Rutgers University.

In the research previously conducted in conjunction with the FAA Center of Excellence for the Computational Modeling of Aircraft Structures, we developed a methodology to place segmented piezoelectric sensors on beams and plates. These sensors are manufactured as thin films and they can be cut into any shape and then glued on to a surface. We conducted a variety of analyses regarding the size, location and number of sensors.

In the research funded by grant 97-G-006, we continued with our efforts to extend the results of our previous research to circular cylindrical shells, with the objective of developing piezoelectric vibration measuring devices for an aircraft fuselage.

The extension of the previously developed theories to shells presented a tremendous challenge, because of the curvature of the shell, as well as the different boundary conditions encountered. We considered the task of developing a shell model with which we could use piezoelectric sensors. Because of the complexity of the mathematical model, most shell analysis is based on approximate solutions obtained by a finite-element analysis. This is true for even the simplest shell models. A disadvantage of such an analysis is that the higher modes become inaccurate, affecting the accuracy of the sensor analysis.

In our research, we took advantage of existing computational advances, such as symbolic manipulation software, and generated the characteristic equations associated with the shell modes. We then took these characteristic equations and solved them using Matlab. Hence, we were able to obtain exact solutions and exact eigenvalues and eigenfunctions. Development of this procedure constituted a substantial portion of the research. We did this analysis for a variety of boundary conditions and compared the results with reported experimental results. The matches we obtained were very close to each other.

We then used the exact (closed-form) eigensolutions of the shell modes and conducted an analysis on the number and location of piezoelectric sensors. We analyzed the modal information that could be obtained from the sensors' output. This analysis was based on the concept of modal filtering that was developed by H. Baruh a number of years ago. We conducted a variety of sensitivity studies involving number and location of the sensors. We studied the effects of the curvature of the sensors, which results from attaching them to the shell surface.

As a result of the analyses conducted in this research, we wrote two papers. Both papers have been published. They are listed below:

J. Callahan and H. Baruh, "Modal Sensing of Circular Cylindrical Shells Using Segmented Piezoelectric Elements," *Smart Materials and Structures*, Vol. 8, 1999, pp. 125-135.

J. Callahan and H. Baruh, "A Closed Form Solution Procedure for Circular Cylindrical Shell Vibrations," *International Journal of Solids and Structures*, Vol. 36, 1999, pp. 2973-3013.

In addition, the graduate student who worked in this project, Joe Callahan, successfully defended his dissertation and was awarded the Ph.D. degree in Mechanical and Aerospace Engineering by Rutgers University in November, 1997. The abstract of his dissertation is included with this report, together with copies of the two articles described above.

There were no other collaborators in this project, other than H. Baruh and J. Callahan. No patents were applied for and there were no inventions. In the future, we hope to extend this research to actual models of the fuselage, and develop procedures for monitoring the structural integrity of aircraft. We also would like to address the issue of noise control in aircraft.

ABSTRACT OF THE DISSERTATION

Cylindrical Shell Vibrations: Closed-Form Analysis and Measurement via Piezoelectric Films

by Joseph Thomas Callahan

Dissertation Director: Professor Haim Baruh

A systematic procedure for obtaining the closed form eigensolution for thin circular cylindrical shell vibrations is presented which utilizes the computational power of existing commercial software packages. For cylindrical shells, the longitudinal, radial, and circumferential displacements are all coupled with each other due to Poisson's ratio and the curvature of the shell. For beam and plate vibrations, the eigensolution can usually be found without knowledge of the absolute dimensions or material properties. For cylindrical shell vibrations, however, one must know the relative ratios between shell radius, length, and thickness, as well as Poisson's ratio of the material. The mode shapes and natural frequencies can be determined analytically with numerically determined coefficients for a wide variety of boundary conditions, including elastic and rigid ring stiffeners at the boundaries. Excellent agreement is obtained when the computed natural frequencies are compared with known experimental results.

Next, thin piezoelectric films are used as sensors to detect vibration of circular cylindrical shells. Rather than using complicated sensor shapes for modal filtering, simple rectangular shapes were used, leaving the measurement filtering to full order modal observers. Simulations indicate that decreasing the magnitude of the real part of the observer gain leads to slower convergence but to the desired mode. Larger

values lead to faster convergence but to the actual sensor measurements, indicating that little signal filtering had time to occur. Increasing the number of sensors also improves observer performance provided that they are placed intelligently on the shell. If a sensor cannot adequately detect the mode which it was intended to sense, sensor output cancelation may affect the behavior of all modal observers. The contribution of different mode types within different frequency bands is also investigated, as well as the determination of an adequate number of vibrational modes to include in the simulations.